

YOU MAY THINK OF SCOPE PROBES AS SIMPLE, AND MANY ARE—BUT NO MEASUREMENT CAN BE BETTER THAN THE PROBE. THE WRONG PROBE NOT ONLY CAN DISTORT YOUR SIGNALS, BUT ALSO CAN MAKE YOUR CIRCUIT MISBEHAVE.

Are you measuring your circuit or your scope probe?

DESIGNERS OF OSCILLOSCOPES have made great strides in improving the instruments' power, accuracy, and ease of use. Nevertheless, achieving the units' specified performance depends on careful equipment selection and operation. A key part of a modern oscilloscope is the probe—an accessory that is all too easy to overlook.

The scope probe is a crucial link in the measurement chain. The probe can affect both your measurement results and the circuit under test and is more than just a signal conduit between the circuit under test and the scope. As part of the measurement chain, the probe affects both measurement results and circuit-under-test operation. All probes present resistive, inductive, and capacitive loading; the challenge is to ensure that these effects stay within acceptable limits. The main source of probe-related measurement errors is capacitive loading. Resistive loading is usually the least worrisome of the three effects because it is least likely to induce nonlinear behavior in your circuit. Although excessive current drain can cause nonlinear response, such response usually isn't a problem when you use a 10-M Ω probe. The most common resistive-loading difficulty results from the voltage divider that consists of the circuit's output resistance and the probe's own resistance:

$$V_{\text{MEASURED}} = V_{\text{ACTUAL}} \times \frac{R_{\text{PROBE}}}{R_{\text{SOURCE}} + R_{\text{PROBE}}},$$

where R_{SOURCE} is the output resistance of the circuit under test.

The lower the probe's resistance relative to R_{SOURCE} , the more that probe loading reduces the amplitude of the measured waveform (Figure 1). For instance, if R_{SOURCE} is 1 M Ω and R_{PROBE} is 10 M Ω ,

the measured amplitude is roughly 9% less than the actual value. If, on the other hand, R_{PROBE} is only 1 M Ω , the measured amplitude is 50% percent lower.

INDUCTIVE LOADING

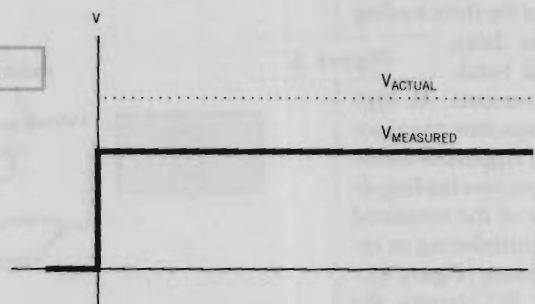
Inductive loading appears as ringing in the observed signal (Figure 2). The source of the ringing is the LC circuit, which comprises the probe's internal capacitance and the ground lead, and the probe-tip inductance. The ground inductance includes the inductance of any jumper wires you may have soldered onto the board to facilitate probing (Figure 3).

The ringing frequency of a simple LC circuit is:

$$F_{\text{RINGING}} = \frac{1}{2\pi\sqrt{LC}}.$$

If the rise time of the waveform is short enough to stimulate this ringing, the ringing appears as part of your captured waveform. For instance, to calculate the ringing frequency that the ground lead causes, you can assume that the probe's ground lead has an inductance of approximately 25 nH/in. Therefore, a probe with a capacitance of 8 pF and a 6-in.

Figure 1



Resistive loading lowers the amplitude of the observed signal without altering its shape.

ground lead has a ringing frequency of approximately 145 MHz:

$$F_{\text{RINGING}} = \frac{1}{2\pi\sqrt{(25 \text{ nH})(6)(8 \text{ pF})}} = 145 \text{ MHz.}$$

Consequently, using this probe to measure any waveform with a rise time of less than roughly 2.4 nsec can result in ringing:

$$T_{\text{RISE}} = \frac{0.35}{\text{BW}} = \frac{0.35}{145 \text{ MHz}} = 2.4 \text{ NSEC,}$$

where BW=bandwidth.

The probe design minimizes the probe's own capacitance, and the probe comes with a fairly short ground lead. (Some probes add a ferrite bead to the ground lead to reduce ringing. For this feature, you pay the price of increased ground impedance, which reduces the probe's common-mode rejection.) Inductive loading isn't usually a problem unless you try to measure signals whose frequency components exceed the probe's bandwidth or you get too creative with the ground or tip connection.

Here are two hints to help you recognize inductive loading problems: First, ask yourself whether ringing is likely to be a problem for the measurements you are making, based on signal frequencies, accuracy requirements, and other measurement variables. Second, check to see if reducing the length of either the ground lead or any added probing wires reduces the apparent resonant frequency. If so, you probably have a problem with inductive loading.

CAPACITIVE LOADING

Capacitive loading, the most troublesome of the three loading effects, affects delay, rise-time, and bandwidth measurements. At high frequencies, capacitive reactance can also affect amplitude measurements. Capacitive loading alters the shape of the measured waveform by introducing an exponential response (Figure 4).

For simple RC circuits, the time constant of this exponential response is approximately equal to:

$$T_{\text{RISE}} = 2.2 \times R_{\text{TOTAL}} \times C_{\text{IN}},$$

where C_{IN} is the combined capacitance of the probe and the scope and R_{TOTAL} equals:

$$R_{\text{TOTAL}} = \frac{R_{\text{IN}}R_{\text{SOURCE}}}{R_{\text{IN}} + R_{\text{SOURCE}}}$$

This time constant sets an upper limit on the rise time of any signal you measure. For a circuit with output resistance of 100Ω, for instance, a probe with 1-MΩ resistance and 8-pF capacitance imposes a rise-time limit of 1.8 nsec (a bandwidth of approximately 200 MHz). Your signal may rise faster, but you won't see it with this probe.

Measurement errors are only half the story with capacitive loading, however. Capacitive-loading effects on circuit performance can lead you down blind alleys, creating apparent problems that don't exist and hiding problems that do exist. If you've ever attached a probe to a malfunctioning circuit only to have the circuit spring to life, you've experienced this phenomenon. Capacitive probe loading can attenuate glitches, reduce ringing or overshoot, or slow an edge just enough

that a setup- or hold-time violation no longer occurs. Conversely, capacitive loading can make a functioning circuit look out of whack.

The most vexing aspect of probe loading is that unless you know the actual (and not just the theoretical) size and shape of your signal, you probably can't tell whether probe loading is affecting your measurement. The solution is to make sure that you correctly use the right probe for every application.

Compromise is implicit in any discussion of resistive and capacitive loading. You have to improve one aspect of a probe's performance at the expense of another. The result is an array of probe types, each tuned to specific applications and budgets.

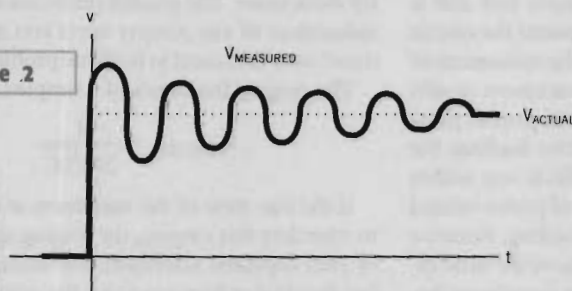
PASSIVE PROBES

For general-purpose, low- to medium-frequency measurements, passive resistor-divider probes are rugged, inexpensive tools. Such probes' biggest disadvantage is that they require high division ratios to achieve low capacitance. These ratios reduce by a factor of 10, 20, or even 100 the signal level that the probe delivers to the scope input. If your scope doesn't automatically scale its display to compensate for the reduction, you need to do the scaling yourself every time you read values from the display.

Low-impedance resistor-divider probes offer low capacitive loading and wide bandwidth at the cost of heavy resistive loading. Typical applications include low-voltage signals, such as ECL circuits and 50Ω transmission lines. Low capacitive loading makes low-impedance resistor-divider probes great for timing measurements. When you use these probes, though, avoid driving the circuit under test into nonlinear operation (Figure 5).

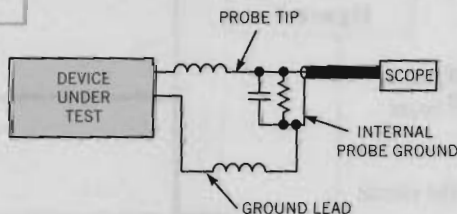
High-resistance passive-divider probes are the most rugged type. They offer wide dynamic range and enough resistance to match the scope's input impedance. The drawback is heavy capacitive loading and somewhat lower bandwidth than that of low-imped-

Figure 2



Inductive probe loading adds ringing to the signal you're trying to measure.

Figure 3



The L-C circuit formed by the probe's internal capacitance and both tip and ground lead inductance is a potential source of ringing.

ance probes. All in all, high-resistance passive probes are a great choice for general-purpose troubleshooting on most circuits.

ACTIVE PROBES

For high-frequency applications that demand precision across a broad frequency range, active probes are the way to go. They cost more and are limited to a few tens of volts of input, but they significantly reduce capacitive loading.

FET active probes used to provide higher input resistance than bipolar active probes, although it's now difficult to tell the difference between the two in this respect. FET probes also feature wide bandwidth. The chief disadvantages are cost and size. FET probes are good choices for ECL, CMOS, and GaAs circuits; analog circuits; transmission lines; and circuits with source resistance lower than 10 k Ω .

Bipolar active probes offer high input resistance (although older models usually can't match FET probes), low input capacitance, and good tolerance to electrostatic discharge. Limited dynamic range and size are bipolar probes' major drawbacks.

You're probably not going to design a scope probe in the near future, but knowing a few design basics helps you to understand why some probes solve the capacitance problem better than others do. If you are in the habit of building your own probe devices, these guidelines should be particularly useful.

On the electrical side, a good design carefully considers the entire signal path, from the device under test, through the probe and all of its accessories and cables, to the scope input circuits. One recommendation on the wise choice and use of probes is to select probes that are compatible with your scope and accessories that are compatible with your probe. The reason stems from an integrated view of the measurement system: Components that are designed together shine together.

MECHANICAL DESIGN

In probes, mechanical design drives electrical performance. Good mechanical design strikes a balance between min-

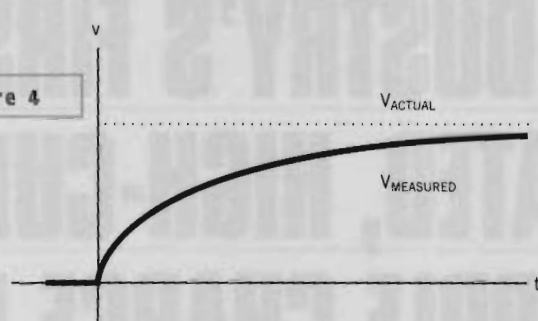


Figure 4
Capacitive probe loading alters the shape of the waveform by introducing an exponential response.

imizing stray tip capacitance and meeting other performance goals, such as size, weight, and ruggedness. A probe's physical packaging can have a major effect on the amount of capacitance the probe inserts into the measurement chain. Mechanical design is particularly significant for active probes, because these probes' mechanical structure can contribute more capacitance than the electrical circuitry can.

The primary goal in mechanical design is to isolate the ground and the input signal as much as possible. Several guidelines help designers achieve this goal:

- When two conductors run parallel to each other, reduce the distance between the input signal and the ground.
- When the two conductors are coaxial, increase the ratio of the ground collar's inner diameter to the input signal's pin or socket diameter.
- Choose a dielectric material that exhibits low relative permittivity.
- Decrease or eliminate the length

over which the two conductors are coaxial or parallel to each other.

Two coaxial probe-tip schemes illustrate these design choices. In **Figure 6**, the ratio of D_2 to D_1 is small. The minimal dielectric material between the input pin and the ground increases the capacitance. In addition, the length over which the two signals overlap, L , even further boosts the capacitance.

The equation for capacitance in a coaxial cylindrical conductor helps explain the situation:

$$C = \frac{2\pi(8.854)\epsilon_r L}{\ln\left(\frac{D_2}{D_1}\right)} [\text{pF}],$$

where ϵ_r is the relative permittivity of the dielectric material, and L is in meters. You can see that lowering ϵ_r or increasing the ratio of D_2 to D_1 lowers the capacitance.

Now, compare the design in **Figure 7**. The larger diameter of the ground collar and the smaller input pin combine to lower the C of the coaxial system. In addition, the ground collar does not overlap the input pin.

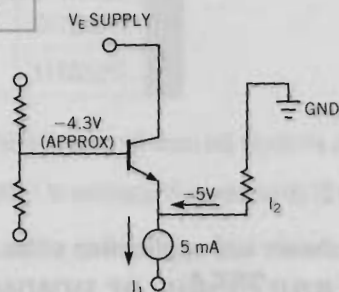
As with every design, there are trade-offs. For instance, moving the ground collar too far from the input pin requires lengthening the grounding accessory, which can degrade the signal. This example illustrates why carefully considering the entire signal path—from the device under test, through the probe, to the scope—ensures the most accurate measurements.

MINIMIZING CAPACITIVE LOADING

You may conclude that scope-probe design is a complicated engineering challenge. Nevertheless, some practical guidelines suggest how to minimize capacitive loading.

Select the right probe for your scope and for the job at hand. It's unwise to purchase a scope for thousands of dollars and then attempt to save a few dollars by using an inexpensive and inferior probe. (A still worse idea is hooking up a grimy old probe that's been rolling around your desk drawer for years.) If you need to justify expenditures for good probes, consider the time that mis-

Figure 5



NOTES: NET CURRENT IN TRANSISTOR $I_1 - I_2 = 0$.
NO CURRENT, NO GAIN.

The heavy resistive loading presented by low-impedance probes can drive circuits into nonlinear operation.

leading measurements can waste and how much unhappy customers and warranty expenses can cost your company.

If possible, choose a probe that matches your scope and probe interface. Today's leading scopes incorporate probe interfaces that provide probe power, configure the instrument, and even control such probe features as offset. Moreover, a scope manufacturer that approves a probe for use with a particular scope has tested the combination and validated it as part of an integrated measurement system.

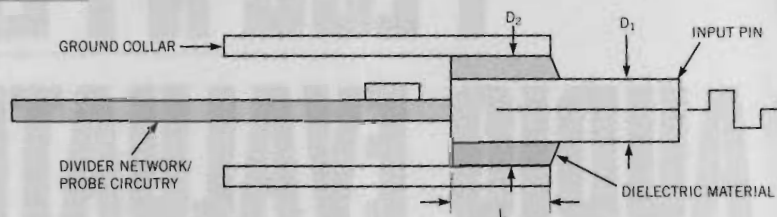
Use only the accessories designed for your probe. Like a scope and its approved probes, these accessories are part of a cohesive system that optimizes performance. Keep in mind that common kludges, such as bits of wire soldered to boards after production to create test points, can drastically degrade measurement results.

THE LAWS OF PHYSICS STILL HOLD

Remember basic electronics principles. Consider what each measurement is supposed to achieve. Can the circuit drive the probe? What is the probe's reactance at the frequencies you're trying to measure? Pay attention to the probe performance specifications.

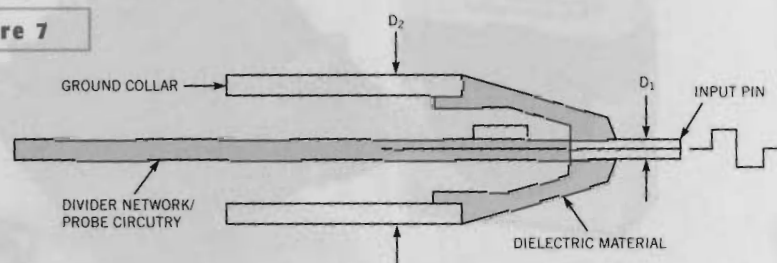
If necessary, modify the circuit to achieve more accurate measurements. One example is building in a divider network with a 50Ω termination to create a voltage drop that you can measure without adversely affecting the circuit. In fact, consider designing test points or probe

Figure 6



This coaxial probe-tip configuration presents a large capacitive load.

Figure 7



This mechanical design reduces probe-tip capacitance.

sockets onto your board to provide good physical and electrical connections for testing and troubleshooting. As the cost of bad measurements increases with complex, expensive systems, for instance, the relative cost of these extra components decreases.

Take advantage of the scope's probe-compensation capabilities. If your scope can automatically compensate for the performance of approved probes, by all means use this feature. Otherwise, use manual compensation to adjust the probe's capacitance (Figure 8).

If any doubt exists, use several probes, such as an active and a passive probe, and compare effects, both on the measurement results and on the circuit's overall operation.

Your best measurement can never be better than your probe, so wisely choosing and using probes only makes sense. With the right probe married to the right scope, you're well on your way to better measurements. □

AUTHORS' BIOGRAPHIES

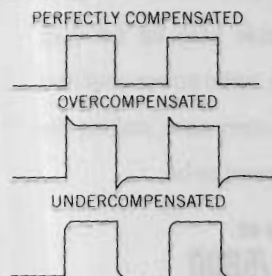
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Figure 8



Manual probe calibration is a simple procedure. Use the scope's calibration signal and adjust the probe's capacitance until you see a perfect square wave.